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Original Research Article

Optimization of multi-slot coaxial antennas for microwave thermotherapy based on the S_{11}-parameter analysis

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ABSTRACT

The underlying aim of presented article is to determine the optimal location and sizes of the air gaps inside a multi-slot coaxial antenna with 50-ohm feed based on the S_{11}-parameter characteristics of microwave applicator to get the best antenna impedance matching to the treated tissue. The next step is the selection of the levels limits of the antenna input power, for which temperature of the tissue do not exceed known therapeutic elevations for microwave therapies at hyperthermic and ablation temperatures. The proposed approach provides a relatively simple method for optimization of the location and size of slots in the antenna structure. The proper choice of limit values of total antenna input power enables appropriate adjustment of temperature of the target tissue to preserve optimal cancer treatment.

1. Introduction

Supraphysiological temperatures above 40 °C can induce serious disruptions in living human tissues at the molecular, cellular, and structural levels which may have a vital importance during the heat therapy [1]. Application of heat into the tissues for therapeutic purposes can be delivered by the electromagnetic field in radio- (RF) [2,3] or microwave (MV) frequency [4,5], ultrasounds as well as laser energy. Nowadays microwave thermal therapies in different branches and applications are increasingly clinically investigated and tested in various diseases including cancer [6,7]. The most common microwave and RF techniques applied to a tumour tissue heating are associated with the so-called interstitial hyperthermia [8] and thermal ablation [1]. Thermal therapies are using differences in the sensitivity of healthy and pathological tissues. It should be emphasized that changes observed in living tissues depend primarily on the temperature that is used. In hyperthermic temperatures, between 40 °C and 45 °C, the malignant cells are damaged as a result of growing processes of apoptosis and necrosis. At the same time the

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healthy cells are avoided from destruction [6]. Higher temperatures, usually in the range of 50–110 °C, are intentionally leading to irreversible cells destruction or tissue burning during the process of thermal ablation [1,7].

The minimally invasive methods of cancer treatment including interstitial microwave hyperthermia and thermal ablation are performed by placing the needle applicator directly into a tumour. Then the tissue heating via microwaves is used to destroy cancer, satisfactorily [7]. Such antennas have been increasingly employed in oncological practice because of their simple constructions, low costs of production, ease in fabrications and practical applications [9–11]. The interstitial techniques are mainly dedicated to the localized treatment of deep, inoperable tumours, especially hepatic tumour, which cannot be surgically removed due to various medical reasons [7]. The basic limitation of this method is the state of the patient health because the thin antenna is intraoperatively inserted into the body through a percutaneous puncture during anaesthesia [12]. The whole therapeutic procedure takes from few to several minutes depending on cancer type, the total input power of microwave applicator and the antenna operating frequency. What is more, the correctness of the applicator placement in diseased tissue may be verified using ultrasound, computed tomography or other medical imaging techniques [7]. Particularly promising treatment results have been reported in the case of early detected brain, breast, liver, kidney and lung malignant tumours [6,7,13,14]. Importantly, thermal therapies significantly enhance the effectiveness of other simultaneous treatments such as radiotherapy, chemotherapy, immunotherapy, gene therapy and others therapeutic procedures [6,8,15]. It was also found that other minimally invasive techniques utilizing magnetic nanoparticles exposed to RF electromagnetic fields have been widely investigated, recently [16,17].

In the last decade significant development in medical applications of various antennas has been observed. Several kinds of cylindrical applicators have been utilized to perform microwave hyperthermia and ablation of tumours, namely a floating sleeve dipole, robust sleeved [18], double choke [19], triaxial choke, cap-choke, expanded tip wire antennas as well as balun-free helical antennas [4]. Very popular for interstitial heating of malignant tissues are coaxial antennas including single- [20], double- [9] and more air gaps [12]. Importantly, the microwave energy emanates from the antenna slots and was dissipated in the human tissue to heat up the tumour. The coaxial-slot antennas are designed to precisely focus the microwave power on the target tissue and uniform heating near the antenna tip [7,21]. It should be stressed that satisfying heat zones are typically observed at a distance of 3–6 cm from the needle applicator [4,5]. A novel multi-slot coaxial antenna has been firstly proposed in [21], and next it was improved in [10]. Until now, the coaxial cables with periodic slots were analyzed as leaky antennas, what was fully described in [22]. The coaxial antennas could be used alone or arranged together into the array applicator to focus the EM radiation within the tumour [8,13].

There are many different optimization procedures that could be found in literature for antennas utilized in thermal therapies. Paper [18] describes the application of VNSP optimization algorithm for specifying the optimal dimensions and therapeutic features of floating slave antenna for hepatic tumour microwave ablation. Another publication [13] focuses on the optimization problem of excitation frequency of *n*-antennas array surrounding the breast with tumour inside for the ultra-wideband and narrowband microwave hyperthermia treatments. Very interesting solution for optimal trajectory planning during interstitial hyperthermia processes by means of dynamic optimization can be found in [23]. The procedure proposed by authors utilizes the formal Lagrangian technique for derivation of optimality conditions for radiofrequency and microwave ablations.

In this paper the S_{11}-parameter analysis of multiphysics problem on microwave tissue heating with novel concept of multi-slot coaxial antenna with periodic slots has been presented for the first time. The outline of this article can be found in the latest author's conference papers [24,25]. Adding new air slots within the microwave antenna structure have significant impact on the operating characteristics of such applicator, which greatly influences the tissue heating efficiency during the various kinds of interstitial thermal therapies. Many current researchers often forget about this fact and uncritically use the previously published data. They do not take into account the kind of human tissue as well as do not check the applicator dimensions that impact on the scattering parameters of such specific tissue-antenna system. Taking into account the increasing number of periodic slots in the microwave antenna structure requires some unique optimization procedure based on the antenna reflection coefficient presented in the paper. Specifying the S_{11}-parameter distribution at the multi-slot coaxial antenna input is the simplest way to obtain the resonant frequencies that characterize the best antenna-tissue impedance matching. On the other hand, possibly the most excellent antenna efficiency could be achieved by changing location of the air gaps inside the microwave applicator with the same antenna working frequency. The next step is the determination of the limit levels of the microwave antenna input power, for which the temperature within the target tissue do not exceed the therapeutic levels for interstitial hyperthermia and thermal ablation procedures. The proposed two-criteria optimization approach is unique and allows the optimal dimensions of the multi-slot coaxial antennas to be estimated for conformal, localized cancer treatment as well as for prediction of the tissue temperature profiles in the case of changing number of periodic slots within microwave needle applicator. It should be emphasized that a number of modern researchers have validated similar models with various experiments on phantoms [14] or animal tissues [5,20] as well as the other clinical trials [15] and different numerical methods [23,26].

2. Model definition

The presented interdisciplinary issue is based on the model for microwave cancer therapy developed by [27]. The coaxial-slot antenna with single radiating aperture has been expanded into proposed multi-slot coaxial antenna with periodic slots as illustrated in Fig. 1. The microwave antenna is composed of two coaxial conductors separated by the dielectric with a 50-ohm feed, which are enclosed together in plastic catheter for

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